Model of Time and Space Distributions of Rainfall in Arizona and New Mexico

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ABSTRACT

Rainfall data from two dense rain gage networks, several small groups of rain gages, and National Weather Service (NWS) rain gages are used to describe the occurrence and depth-area distribution of rainfall and to develop a rainfall simulation program (model) for Arizona and New Mexico. Depth-area rainfall distribution is described by an assumed cellular thunderstorm structure, with verification limited to comparison of simulated and actual total rainfall patterns. Simulated rainfall is convenient to use in hydrologic models when long term rainfall records are unavailable. If point records are available, they can be used to verify the model.

The program output includes accumulated seasonal rainfall for any designated point (gage), point totals for individual events for isohyetal mapping, starting and ending times for all events, and Thiessen weighted watershed averages. The output can be used directly to estimate peaks and volumes of runoff for very small watersheds (up to 100 hectares), and indirectly for larger watersheds with appropriate routing methods. Since the rainfall is distributed both in time and space, simulations of several years of record could be used to provide probabilities of wet and dry sequences to evaluate the chances of success for range renovation programs and could aid ranchers in overall planning of range management programs.

KEYWORDS: Rainfall, hydrology, model, semiarid, simulation, precipitation, thunderstorm, rain gage, range, watershed, computer.

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MODEL OF TIME AND SPACE DISTRIBUTION OF RAINFALL IN ARIZONA AND NEW MEXICO

By H. B. Osborn, E. D. Shirley, D. R. Davis, and R. B. Koehler

INTRODUCTION

Rainfall is an input used in most hydrologic models that estimate runoff volumes or peak discharge. Simulated rainfall is convenient to use in the development of such models because long and complete precipitation records, typical of areas where the model is to be applied, can be quickly generated. Simulated rainfall is necessary in applying such models to areas where rain gages are scarce or nonexistent or where historical records are too short. Where one or more point records are available, they can be used to verify models or to manipulate parameters in the models.

In this paper, rainfall data from two dense rain gage networks, several small groups of rain gages (fig. 1), and National Weather Service (NWS) rain gages are used to develop a rainfall simulation program for Arizona, New Mexico, and similar semiarid regions. We first describe the rainfall occurring in these areas and then present a simulation program involving several rainfall models. Hydrologic assumptions and simplifications in the program subroutines are discussed, and sample program output is described.

SELECTED RELATED RAINFALL STUDIES

Osborn and Lane (*1969*) studied the relative sensitivity of rainfall variables and watershed characteristics on runoff from intense, short-duration thunderstorm rains. They found that, for four very small watersheds (4 ha and less), runoff volume was most strongly correlated to total rainfall and peak discharge was best correlated to maximum 15-min rainfall. Total runoff was also highly correlated to maximum 15-min rainfall, because the maximum 15-min rain-

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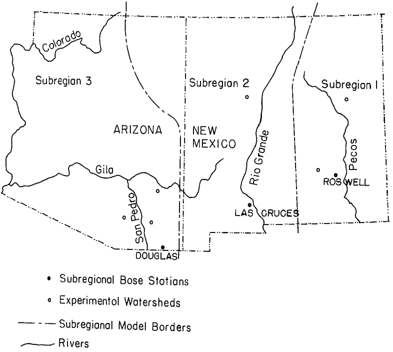

Figure 1.--Region and subregions covered by regional rainfall model.

fall is usually related to storm total. Rainfall dominated the relationships. Differing watershed characteristics did not add significantly to estimates of peaks or volumes of runoff, but the watersheds studied were quite similar.

Fogel (*1969*) reported on the effects of storm rainfall variability on run-ff from small watersheds in the Southwest. He pointed out that runoff is a mplicated process and becomes more complicated when the input is highly in-nse, short-duration thunderstorm rainfall of limited areal extent. Most cur-nt methods for estimating runoff volumes require knowledge of only total rain-l depth, which can lead to significant errors in estimating runoff.

Duckstein et al. (*1972*) introduced a stochastic model of runoff-producing fall for summer-type storms in the southwestern United States. They pointed that modifications in runoff can occur either naturally or through human in-ces, and that in either case rainfall input must be properly modeled to de-

termine actual changes in runoff with changes in watershed characteristics. They consider summer rainfall as an intermittent stochastic phenomenon and obtained the probability distribution of areal rainfall by convoluting a Poisson distribution for the number of events with a geometric or negative binomial probability of rainfall amount. They then used their rainfall model in several rainfall-runoff relationships to illustrate the practical value of the method.

Osborn and Laursen (*1973*) identified the differences in the runoff-producing characteristics of the airmass thunderstorms common to Arizona and western New Mexico and the frontal convective rains more common to eastern New Mexico and western Texas. They found that peak discharge from semiarid rangeland wastersheds larger than 2 km^2 in southeastern Arizona was best correlated to maximum 30-min rainfall (as opposed to maximum 15-min rainfall for very small watersheds), which they referred to as the core of runoff-producing thunderstorm rainfall. The simulation program presented in this paper is based on the concept of a core of runoff-producing rainfall and can be used for watersheds of 2 km^2 and larger.

RAINFALL DEPTH-AREA DURATION

The USDA Southwest Rangeland Watershed Research Center (SRWRC) has operated the 150-km^2 Walnut Gulch Experimental Watershed in southeastern Arizona and the 174-km^2 Alamogordo Creek Experimental Watershed in eastern New Mexico since 1954 (fig. 1). Currently, there are about 95 and 65 recording rain gages, respectively, on the two watersheds, although not all of the gages have been operated during the full period of record. Also, the SRWRC operated several small experimental watersheds near Safford, Ariz., and Albuquerque, N. Mex., through 1976, and near Ft. Stanton, N. Mex., from 1966 to the present. Data collected from these networks are used to illustrate the range and variability of runoff-producing characteristics of thunderstorm rainfall.

Regional differences in rainfall amounts and intensities in arid and semiarid regions have been widely investigated; however, quantitative descriptions of these differences, usually as depth-duration frequencies, generally have ignored differences in the storm system that generated the rainfall, and have lumped together essentially different storm populations. For example, thunderstorm rainfall occurring in the arid and semiarid regions of the Southwest can be divided roughly into rains occurring from airmass thunderstorms and from frontal-convective thunderstorms.

Differences in runoff-producing characteristics between and within the two thunderstorm types--airmass and frontal-convective--are best illustrated using data from dense rain gage networks on the Walnut Gulch and Alamogordo Creek watersheds.

Airmass Thunderstorms

The extreme spatial variability of airmass thunderstorms, which is typical in southeastern Arizona, is illustrated by an isohyetal map of total storm rain-

fall for the event with the maximum 1-hr rainfall on Walnut Gulch (fig. 2). Maximum observed point rainfall was 88 mm, with depths decreasing rapidly, but unevenly, from the maximum point. All surrounding gages recorded less than 70 mm of rainfall. An area of less than 2 km^2 received more than 70 mm of rainfall. In one direction, depths were less than 25 mm within 3 km^2 of the maximum.

The durations of runoff-producing thunderstorm rains are also extremely variable. For example, for the storm of September 10, 1967, rainfall lasted up to 70 min at some gages, but only 45 min at the storm center. Intense rainfall usually lasts for less than 20 min at any one gage. The major events last longer than the smaller events, but do not necessarily have greater intensities.

Many rainfall-runoff relationships are based on average rainfall for a given duration. Amounts for shorter durations are derived by multiplying the longer duration amount by some given fraction. The recommended fractions are often based on average storm values, which may be misleading for design purposes for the major more infrequent events. Ratios of rainfall depths for short duration to 1-hr amounts for 37 events of 25 mm or more on Walnut Gulch are shown in table 1. The average ratio of 15-min and 30-min depths to 1-hr depths are 0.66 and 0.88, respectively, for the 37 storms, but only 0.41 and 0.72, respectively, for the record maximum 1-hr event. If, for example, the 1-hr, 100-yr maximum point rainfall was 88 mm, the 30-min rainfall based on an average value of 0.88 would be 77 mm rather than 62 mm. The two values entered into the same rainfall-runoff model would give significantly different estimates of the 100-yr peak discharge. Whereas average or generalized values might be acceptable, on the average, for runoff design for the more common events, they might lead to overestimates of rainfall for individual events.

Table 1.--*Ratio of storm rainfall depth for various durations to 1-hr rainfall for 37 storms of greater than 25 mm for Walnut Gulch.*

	Duration (min)					
	5	10	15	20	30	60
Average	0.28	0.50	0.66	0.76	0.88	1.0
Range	0.15-0.54	0.28-0.77	0.38-0.92	0.47-0.96	0.66-1.0	---
Sept. 10, 1967[1]	0.17	0.31	0.41	0.53	0.72	1.0

[1]Maximum 1-hr point rainfall (88 mm); the only measured 1-hr amount greater than 75 mm on Walnut Gulch (1955-77).

Depth-area curves for maximum 1-hr rainfall for the storms of September 10, 1967, July 22, 1964, and August 17, 1957, on Walnut Gulch (dashed lines in lower portion of fig. 3) again illustrate the limited areal extent of airmass thunderstorm rainfall.

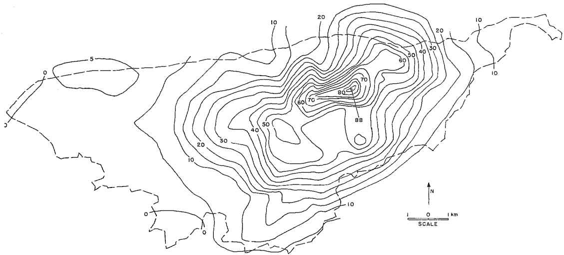

Figure 2.--Isohyetal storm rainfall map of September 10, 1967, Walnut Gulch. Each contour represents 5 mm of rainfall.

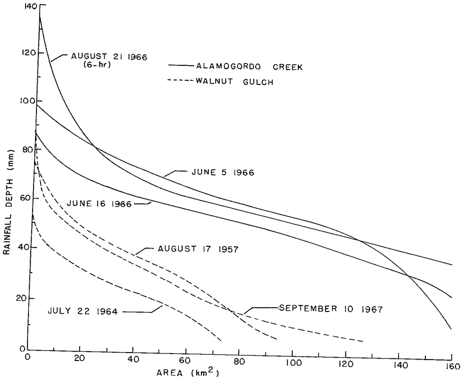

Figure 3.--Depth-area rainfall curves for selected events for Walnut Gulch and Alamogordo Creek.

Frontal Convective Thunderstorms

Frontal-convective thunderstorms, which are common in eastern New Mexico, can cover more area, last longer, and produce greater amounts of rainfall for similar durations than airmass thunderstorms. The more massive nature of some frontal-convective thunderstorms is illustrated by an isohyetal map of total storm rainfall for the event with the maximum recorded 1-hr rainfall on Alamogordo Creek (fig. 4). Rainfall ranged from 4 mm to 103 mm, with four gages recording 100 mm of rain or more. Almost all rain fell in 1 hr. Although the storm was more massive than an airmass thunderstorm, it was reasonably well centered on the watershed, and apparently extended for only short distances outside the watershed. Unfortunately, the network was not large enough to encompass the entire storm.

Ratios of rainfall depths for short durations (up to 1 hr) for 37 airmass and frontal-convective events of over 25 mm on Alamogordo Creek are shown in table 2. The average ratios of 15-min and 30-min depths to 1-hr depths are 0.56 and 0.81, respectively, for the 37 storms (as compared with 0.66 and 0.88 for Walnut Gulch). The two events with maximum 1-hr point rainfall are also shown. Rainfall for durations of 5 to 30 min was about average for the June 5, 1960, storm and considerably below average for the August 21, 1966, storm, indicating that intense rainfall may last longer on some occasions than has been experienced on Walnut Gulch. Again, not enough data are available to be certain of this or to assign probabilities to events of the magnitude of June 5, 1960, on Alamogordo Creek.

Table 2.--*Ratio of storm rainfall depth for various durations to 1-hr rainfall for 37 storms of greater than 25 mm for Alamogordo Creek*

	Duration (min)					
	5	10	15	20	30	60
Average	0.25	0.41	0.56	0.68	0.81	1.0
Range	0.13-0.47	0.25-0.67	0.35-0.98	0.45-0.99	0.63-0.99	---
June 5, 1960[1]	0.20	0.39	0.54	0.69	0.84	1.0
August 21, 1966[2]	0.20	0.34	0.46	0.55	0.68	1.0

[1]Maximum 1-hr point rainfall (103 mm) on Alamogordo Creek (1955-77).

[2]Maximum 1-hr point rainfall (91 mm) for second greatest event on Alamogordo Creek.

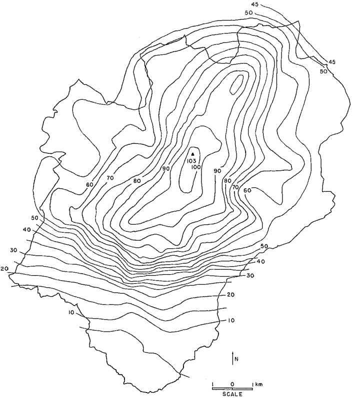

Figure 4.--Maximum 1-hr rainfall, June 5, 1960, Alamogordo Creek. Each contour represents 5 mm of rainfall.

Differences on rainfall volumes for observed maximum 1-hr rainfall are illustrated with rainfall from the maximum events on Walnut Gulch and Alamogordo Creek (tables 3 and 4). The more massive nature of frontal-convective storms on Alamogordo Creek is apparent. For example, the areal extent at the 50-mm isohyets for the Walnut Gulch and Alamogordo Creek storms, respectively, are about 12 and 148 km^2. The total volume of rainfall for the Alamogordo Creek storm was at least three times that of the Walnut Gulch storm, although we could only estimate total areal values.

Table 3.--*Maximum 1-hr rainfall volumes within selected isohyets for storm of September 10, 1967, on Walnut Gulch*

Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)	Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)
80	0.2	0.2	35	38.5	18.8
75	.6	.5	30	47.7	21.6
70	1.4	1.1	25	57.0	24.1
65	2.6	1.9	20	[1]66.8	[1]26.3
60	4.1	2.8	15	[1]79.3	[1]28.5
55	6.7	4.3	10	[1]104.0	[1]31.6
50	12.4	7.3	5	[1]124.0	[1]33.1
45	22.8	12.2	0	[1]155.0	[1]33.9
40	31.1	15.8			

[1]Partial storm areas and volumes recorded only within the rain gage network.

Table 4.--*Maximum 1-hr rainfall volumes within selected isohyets for storm of June 5, 1960, on Alamogordo Creek*

Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)	Isohyet (mm)	Area (km^2)	Volume (10^6 m^3)
95	2.3	2.2	45	[1]153	[1]101
90	8.0	7.1	40	[1]154	[1]102
85	16.3	14.8	35	[1]155	[1]102
80	25.4	22.2	30	[1]156	[1]102
75	34.2	29.1	25	[1]157	[1]103
70	43.8	36.1	20	[1]159	[1]103
65	66.8	51.8	15	[1]161	[1]103
60	97.6	71.0	10	[1]162	[1]103
55	124	86.0	5	[1]164	[1]104
50	148	98.5	0	[1]174	[1]104

[1]Partial storm areas and volumes recorded only within the rain gage network.

Depth-area curves for maximum 1-hr rainfall for the storms of June 5, 1960, and June 16, 1966, and for maximum 6-hr storms for August 21, 1966, on Alamogordo Creek are plotted along with depth-area curves for "record" Walnut Gulch storms (fig. 3). The curves for Alamogordo Creek are much flatter than those for Walnut Gulch. Also, the longer durations plot above the shorter durations, indicating that, for frontal-convective events, storm areas generally increase with increasing depths.

TIME DISTRIBUTION

Because of the nature of airmass thunderstorms, rainfall time distribution both at a point and over a small watershed (up to 150 km^2) for major events has relatively little effect on flood peaks and volumes (Osborn and Laursen, *1973*). This is primarily true because the intense "core" of runoff-producing rainfall occurs as one unit and is much greater than the light rains that often follow and sometimes precede heavy rainfall. Based on Walnut Gulch data, intensities for major airmass thunderstorms are on the order of 125 mm/hr for about 30 min or a little longer, whereas intensities during the mature and dissipating stages are generally more on the order of 2 to 3 mm/hr. Also, intense rainfall tends to begin and end very abruptly.

As an example, histograms of maximum point rainfall for three of the four largest runoff-producing airmass thunderstorms on Walnut Gulch are shown in figure 5. In all four cases, including the one not shown, over 90 percent of the rain fell in less than 60 min, and intensities outside the core of runoff-producing rainfall were too low to cause runoff. In almost all cases on Walnut Gulch, runoff-producing point rainfall lasted less than 60 min.

On the other hand, in eastern New Mexico, where frontal activity in combination with convective heating often affects rainfall, the time distribution of rainfall can have a significant effect on flood peaks and volumes. Histograms of three major runoff-producing events are shown in figure 6. Rainfall is concentrated within 60 min during two of the three events. The third event (on August 21, 1966) was distinctive in that intense thunderstorm rainfall was superimposed on a heavy frontal-type rain with heavy runoff resulting.

STORM MOVEMENT

Stream channels in arid and semiarid regions are generally ephemeral and can abstract large volumes of runoff in the normally dry channels. These abstracting channels add to the complexity of thunderstorm rainfall-runoff relationships. From our observations, storm movement appears to have little effect on major flood peaks for small watersheds. If the storm moves up the watershed, runoff moves more rapidly through the wetted channels, whereas if the storm moves down the watershed, the slower moving early runoff tends to arrive at the outlet at the same time as runoff closer to the outlet. In both cases, peak discharges are similar for similar rains; however, storm movement can significantly affect flood peaks and volumes for smaller events. If the storm moves too rapidly, either across, up, or down the watershed, the reduced surface runoff can be all, or mostly, abstracted in the channels above the watershed outlet.

REGIONAL RAINFALL MODEL

The regional rainfall simulation model is based primarily on two existing computer rainfall models. The first is a stochastic depth-area model of airmass

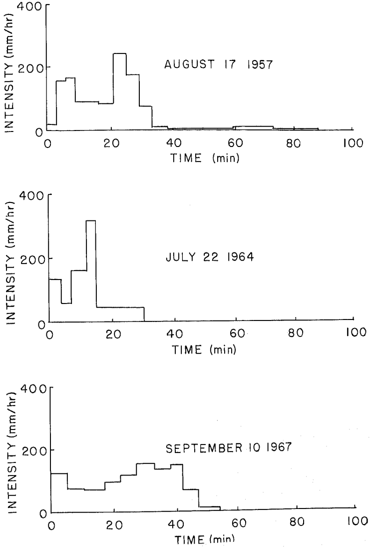

Figure 5.--Histograms of three major runoff-producing events on Walnut Gulch.

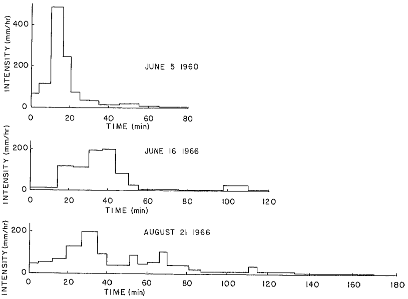

Figure 6.--Histograms of three major runoff-producing events on Alamogordo Creek.

thunderstorm rainfall that was developed with recording rain gage records from the Walnut Gulch Experimental Watershed (Osborn and others, *1972*; Osborn and others, *1974*). The second simulates daily rainfall occurrence in Arizona and New Mexico (Osborn and Davis, *1977*). In addition to revising and adopting these two models, routines were developed to simulate frontal rainfall and to expand the airmass thunderstorm rainfall model to include frontal convective events. The regional model is a set of easily modified subroutines, so changes can be made in the model as more is learned about rainfall in the Southwest.

Input Data

Comparison of NWS rain gage records and topographic features in Arizona and New Mexico suggested the region could be divided into three relatively homogenous

subregions (fig. 1; Osborn and Davis, *1977*). Subregion 1 is eastern New Mexico; subregion 2 is western New Mexico and northeastern Arizona, and subregion 3 is the remainder of Arizona. The program overestimates rainfall occurrences for watersheds below 300 or above 2300 m in elevation; fixed coefficients in the program must be adjusted for watersheds outside these elevation limits. The appropriate subregion must be entered along with the parameters--latitude, longitude, and elevation--representative of the watershed. The relative coordinates of each rain gage (or dummy measuring point), along with Thiessen weights (optional) are also entered.

Probabilities for airmass thunderstorm rainfall are based on seasonal probability curves at base stations in the subregions--Roswell (base station of subregion 1), Las Cruces (base station of subregion 2), and Douglas (base station of subregion 3). The seasonal curves are adjusted automatically when the watershed latitude, longitude, elevation, and subregions are entered.

Thunderstorm rainfall probabilities for SE moisture (explained in the following section) are based on a 2-km^2 watershed and are adjusted upward for larger waterseds. For example, there are, on the average, about twice as many thunderstorms on the 150-km^2 Walnut Gulch watershed than on a 2-km^2 subwatershed within Walnut Gulch.

Rainfall Occurrence

Available recording rainfall records from USDA experimental watersheds and the NWS rain gage network in Arizona and New Mexico were used to develop the rainfall occurrence routine in the regional model (fig. 7; Osborn and Davis, *1977*). Two types of precipitation-producing systems were identified--frontal and airmass--with airmass divided as to the source of moisture. Moist air from the Gulf of Mexico is called SE moisture; moisture from the Pacific and the Gulf of California is called SW moisture. Frontal activity is more likely in

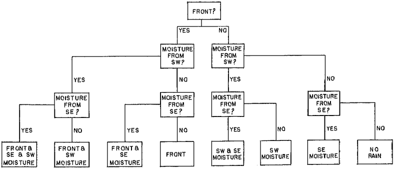

Figure 7.--Simplified schematic of summer rainfall occurrence in Arizona and New Mexico.

eastern New Mexico and northern Arizona than in southern Arizona and southwestern New Mexico, and has a strong latitudinal component, whereas SE moisture is more common in New Mexico, and SW moisture is more common in Arizona. Both have a strong longitudinal component. Elevation is the third significant parameter in the occurrence routine. Daily rainfall occurrences are determined independently for the three systems, and are combined, when necessary, in the depth-area rainfall simulation (to be explained later).

We determined frontal rainfall occurrence by using uniform seasonal distributions based on watershed location and elevation. An element in the frontal subroutine increases rainfall probability on the day after it rains. The chance of rain is reduced to the original fraction after a dry day. The subroutine adjusts for frontal activity that is more common as we move both north and east in the region.

We determined SW rainfall occurrence by using an annual uniform distribution location and elevation. With satellite pictures now available, we may be able to identify significantly different seasonal probabilities in SW rainfall occurrence and to incorporate these differences into the program. The likelihood of SW rainfall occurrence is much greater in Arizona than New Mexico, and the subroutine incorporates this difference. Also, once SW rainfall has occurred, the chance of rain on the following day increases (Osborn and Davis, *1977*).

The SE rainfall occurrence routine is more complex. SE moisture is seasonal, representing the so-called monsoon in the southwest. We chose base stations that appeared representative of each of the three subregions. Daily probabilities are automatically modified by a multiplier based on the watershed location and elevation. In general, SE moisture increases with elevation and decreases as we move north and west, and the subroutine allows for this. Although separate equations were developed in the model to account for persistence in frontal activity and moisture from the southwest, no persistence equation was included for moisture from the southeast.

Several investigators have used Markov chain models to predict point rainfall occurrence. Smith and Schreiber (*1973*) assumed all events were of the same population and fitted daily rainfall occurrences at three stations in southeastern Arizona with a segmented first-order Markov chain model. Woolhiser (*1975*) has proposed a three-parameter mixed exponential Markov chain model of daily rainfall based primarily on data from the Great Plains area. Possibly this model, or a variation, could be adapted to the southwest as a substitute for the more cumbersome empirical equations that are presented here.

Moisture, particularly from the southeast, dominates summer rainfall in southeastern Arizona. Osborn and others (*1972*) modeled storm occurrence as a seasonal Bernoulli random variable based on occurrence of storms of more than 5 mm on Walnut Gulch. Since there was no statistical difference in the persistence pattern for major events between simulated and actual data, the model did not include a persistence equation for southeast moisture.

If a thunderstorm day is simulated, more than one event may occur on that day. Chances for multiple events are based on Walnut Gulch data. Dates and types of rainfall occurrences, simultaneous occurrences, and multiple events are stored for use in the depth-area program routine.

Time Distribution

Thunderstorms have an extremely complex cellular structure in time and space, which is extremely difficult to model without major simplifications. Our program simulates a simplified cellular structure as a vehicle to arrive at storm output, which in turn can be compared directly with real storm data.

If a thunderstorm is indicated, the program first generates a beginning time based on a normal distribution centered at 1700 hr. Each thunderstorm has between 3 and 12 cells with a mean cell distribution of 6. The cells are multiplied by a constant (assumed average cell rainfall duration) to determine the end time for the "runoff-producing" portion of the event (light rain may fall for some time after a thunderstorm, but this nonrunoff-producing rainfall is not included in the model). Individual cells would not necessarily produce runoff, but are assumed to be in the active part of the thunderstorm event.

If the occurrence routine calls for a second event, the program will repeat the routine, but only after determining that the second event begins after the first event ends. Beginning times are generated until this occurs.

Depth-Area Rainfall Simulation

The simplest output in the program occurs on a day with only frontal rain. Frontal rain is generated for a point and assumed uniform over the entire watershed. For larger watersheds, we may add a subroutine to vary rainfall with elevation. Frontal storms must last for at least 3 hr and can extend into the following day.

Many of our assumptions for the dimensions and distribution of the internal components of thunderstorm rainfall have been determined by trial and error until the simulated and real storm outputs are comparable (Osborn and others, *1973*). At this time, we assume depth-area rainfall simulations for SE, SW, and SE/SW occurrences are the same. We assume a constant radius for airmass thunderstorm cells. In the future, we hope to be able to identify significant differences in SE and SW events and to program these differences.

The program will generate a rectangular area enclosing the rain gages (or dummy points) entered into the program and establish a buffer area around the rectangular watershed (fig. 8). The center of the first cell is randomly located somewhere within the buffer (which includes the watershed area). We assume the second cell is up to a cell diameter from the first cell and has a random directional component. The third, fourth, fifth, etc., cells have a directional component based on the direction between the previous two cells. Next, cell center depths are generated independently for each cell. An example of the program at this point is shown in figure 9.

Once the center depths are determined, the rainfall is distributed and accumulated at all designated rain gage or dummy measuring points. Average watershed rainfall is determined from the Thiessen weighting, and can be printed out in the final program. Point event totals are printed out and can

be used to plot isohyetal maps (fig. 10).

When frontal and thunderstorm events are simulated on the same day, the program combines the elements of both storm types. First, frontal rainfall is simulated and distributed to each gage. Then, the cells are simulated as described previously. Based on data from the Alamogordo Creek rain gage network, we assume that cell diameters and depths are greater for the frontal-convective simulation.

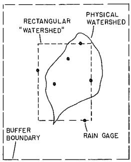

Figure 8.--Rectangular watershed and buffer area created in the depth-area rainfall subroutine.

EXAMPLE OF OUTPUT

The user output can be best described by simulating rainfall in an actual situation. We simulated rainfall on a small (8 km^2) subwatershed (W-11) on the Walnut Gulch Experimental Watershed near Tombstone, Ariz.

There are 10 recording rain gages on or immediately adjacent to W-11. The relative location and Thiessen weight for each gage must be entered into the program (table 5). The program will establish a rectangular watershed and buffer (fig. 8). In practice, most gages are "dummy" locations used to identify the watershed boundaries and to register simulated rainfall at a point. The latitude, longitude, and average watershed elevation also must be entered into the program. The program can be instructed to simulate rainfall for an entire year, or any portion thereof; we have concentrated on the thunderstorm season. A typical season for W-11 is shown in table 6. Rainfall is concentrated in July and August with almost all rainfall occurring from airmass thunderstorms.

Once it has been established that thunderstorm rainfall occurs on a particular day based on a given probability for that day, there is a lesser chance of a second storm occurring, and then a third, and so on. The program will generate a series of rainfall cells starting within the subject watershed or buffer area. In our example, shown in figure 9, the program predicted two

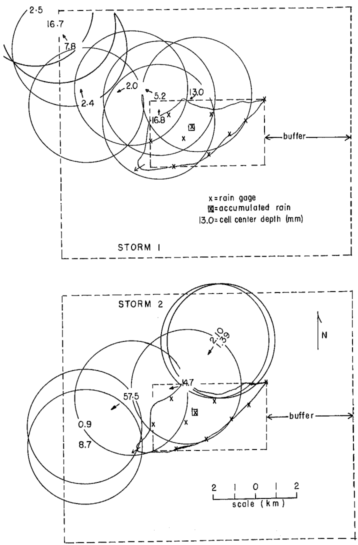

Figure 9.--Simulated storm cell development on a Walnut Gulch subwatershed.

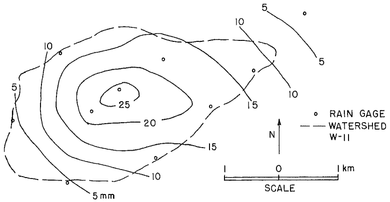

Figure 10.--Isohyetal map of simulated storm rainfall on a Walnut Gulch subwatershed.

Table 5.--*Location of rain gages on or near Walnut Gulch subwatershed W-11*

Gage No.	Inside (I) or outside (O) watershed	X-ordinate (km)	Y-ordinate (km)	Thiessen weight
51	I	6.48	6.28	0.111
89	O	7.34	7.45	.098
90	I	7.95	6.45	.111
52	I	7.52	5.24	.073
54	I	9.26	7.34	.105
88	I	8.44	6.83	.162
56	I	9.15	5.67	.092
94	I	11.79	8.14	.140
55	I	10.91	7.17	.102
91	O	10.14	6.57	.006

thunderstorm events, which lasted from 0900 to 0940 and 2150 to 2220, respectively. In the first event of the day, there were eight cells with center depths ranging from 1.2 to 10.1 mm. In the second event, there were six cells with center depths ranging from 0.6 to 34.5 mm.

Accumulated rainfall is printed out for any selected gage(s). The high and low years and 10-yr mean for a centrally located gage are shown in figure

Table 6.--*Simulated rainfall occurrences for a typical season for Walnut Gulch subwatershed W-11*

Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types	Day	No.[1]	Types
121			149			177			205	1	SE	233	1	SE	261		
122			150			178			206			234			262		
123			151			179			207			235	1	SE	263		
124			152			180			208	1	SE	236	1	SE	264		
125			153			181			209	2	SE	237			265		
126			154	1	SW	182	1	SE	210	1	SE	238			266		
127			155	1	SW	183	1	SW	211			239			267		
128			156	1	SW	184			212			240			268		
129			157			185	1	SW	213	1	SE	241			269		
130			158			186	1	SW	214	1	SE	242			270		
131			159			187	2	SE	215			243			271	2	SW
132			160			188			216			244			272	1	SE
133			161			189	1	SE	217	1	SW	245			273		
134			162			190			218	1	SE, SW	246			274		
135			163			191			219			247			275		
136			164			192			220			248			276		
137			165			193			221	1	SE	249	1	SE, F	277		
138			166			194	2	SE, SW	222	1	SE	250	1	SE	278		
139	1	F	167			195	1	SE, SW	223			251	1	SW	279		
140			168			196			224			252	1	SW	280		
141			169			197	1	SE	225	1	SE	253			281		
142			170			198	1	SE	226			254			282		
143			171			199			227			255			283		
144			172			200			228			256			284		
145	1	SW	173			201	1	SE	229			257	1	SW	285		
146	1	SW	174			202	1	SW	230			258			286		
147	1	SW	175			203	1	SW	231	1	SE	259			287		
148			176			204			232	1	SE	260			288		

[1] Number of thunderstorms on given day.

11. By chance, early season rainfall for both years was below average. In this example, the high year resulted from heavy rains in September. Based on 25 yr of record from Walnut Gulch, such heavy September rains occur on the average of about once every 5 yr, and analysis of Walnut Gulch rain gage data indicates that September rains are not correlated with July-August rainfall. The program can be instructed to print out any or all designated gage accumulations as well as the areal distribution and watershed average for all events.

The program output can be used for many purposes. For example, isohyetal maps can be constructed for any event (fig. 10) or for seasonal or annual precipitation. Thiessen weighted averages can be computed. Average or point watershed rainfall can be used directly as input to hydrologic models to obtain the probability distribution function of peak discharge and storm runoff. The seasonal rainfall distribution at a centrally located gage (or gages) can be used as input for range condition models or to estimate the probable outcome of range renovation programs. The latter may be particularly important, since hydrologic data are usually lacking when range renovation programs are evaluated. Also, model output would be used, for example, to estimate the EI (rainfall energy) factor in the Universal Soil Loss Equation (USLE) and to predict erosion and sediment yields given other appropriate models.

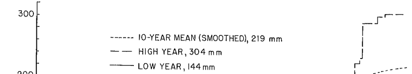

Figure 11.--Smoothed mean and maximum and minimum accumulated seasonal rainfall for 10 yr of simulated rainfall.

SUMMARY AND CONCLUSIONS

Precipitation in Arizona and New Mexico occurs primarily from frontal activity or convective systems or a combination of both. Summer rainfall in the form of thunderstorms is extremely variable both in time and space, whereas

frontal rainfall is more evenly distributed (Osborn et al., *1979*). Models of both the occurrence and areal extent of rainfall are necessarily simplified.

A model has been developed that simulates rainfall occurrence and amounts for ungaged watersheds up to 150 km^2 and elevations between 300 and 2300 m in Arizona and New Mexico. The model is a combination of many subroutines with a number of alternative inputs and outputs. The model simulation includes accumulated seasonal rainfall for any designated rain gage, point totals for individual events, starting and ending times for all events, and Thiessen weighted averages. The model output can be used, for example, to simulate thunderstorm rainfall, which in turn can be used to predict the distribution and magnitude of peak discharges and runoff volumes for ungaged watersheds. The model output can also be used to estimate erosion and sediment yield from small watersheds and as input to more complex range renovation or management models.

Many range management or renovation treatments proposed by ranchers rely heavily on rainfall as the "make or break" variable of the treatment. These treatments could be tested before implementation by simulating rainfall for varying conditions and then determining the corresponding impact on the range management treatment. This preliminary testing could reduce the risk of treatment failure and economic and resource loss.

The program is available by writing to: USDA Southwest Rangeland Watershed Research Center, 442 East Seventh Street, Tucson, Ariz. 85705.

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APPENDIX

The main program, SATDOR (Space and Time Distribution of Rainfall) (fig. 12), is broken down into a number of subroutines (fig. 13). This allows the operator to easily modify specific procedures simply by adding the parts of interest. The function of each subroutine is explained so that the operator will understand its role in SATDOR. To insure consistancy of the sequence, when the program first starts, the day before the start of the season is assumed to have no rain. The program proceeds on a consecutive daily basis.

There are seven major subroutines; three are made up of minor subroutines (fig. 13). The first three are required to generate rainfall occurrence; the next two are used to generate the spatial distribution of rainfall; and the last two are used to determine the temporal distribution of rainfall events. The seven subroutines are:

(1) WSHED - Definition of watershed boundaries and gage locations.

(2) PDF - Probability distributions and parameters for rainfall occurrence defined.

(3) DROM - (Daily Rainfall Occurrence Model) - Generates daily rainfall occurrence record.

(4) SPAR - (Space Parameters) - Spatial parameters defined and calculated.

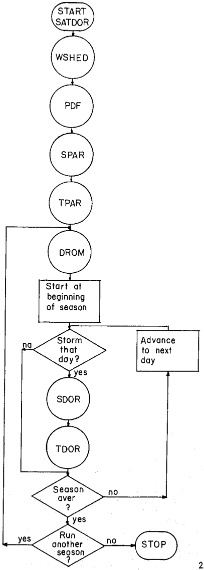

Figure 12.--Flow chart and subroutine locations in SATDOR (Space and Time Distribution of Rainfall).

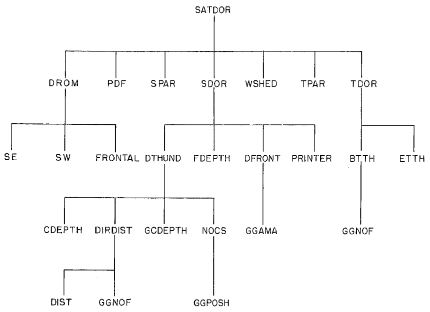

Figure 13.--Subroutine linkage in SATDOR.

(5) SDOR - (Space Distribution of Rainfall) - Spatially distributes rainfall for individual events.

(6) TPAR - (Time Parameters) - Temporal parameters defined and calculated.

(7) TDOR - (Time Distribution of Rainfall) - Distributes rainfall temporally.

WSHED

The WSHED subroutine reads in the rain gage numbers, whether the gages are on the physical watershed, the *x* and *y* coordinates of each gage, and the Thiessen weight of each rain gage. Then, the maximum and minimum coordinates are used to establish a rectangluar rainfall area. Even though the physical watershed is usually some irregular shape, the rain gages will be used to define a rectangle. The rectangular area is computed and printed. A buffer of 4 km is added to each side of the rectangle so that simulated storms may form both outside and inside the watershed (fig. 8). At present, the buffer is constant, but we are investigating whether it should vary with watershed size.

The areal adjustment factor (AAF) is also defined in this subroutine. The AAF affects the probability distribution (P) read in by PDF (see PDF section). The AAF is a multiplication factor that increases rainfall probability (p) with increasing area, but not in direct proportion to areal differences (fig. 14). AAF equals one for watersheds up to 2 km^2, and is varied upward as rain is simulated over larger watersheds. The rainfall probability cannot exceed one.

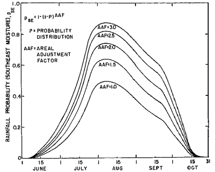

Figure 14.--Method for adjusting SE thunderstorm rainfall probabilities according to watershed area.

PDF

The PDF subroutine reads in data used by the DROM subprograms. These data include the watershed location, elevation, region, season beginning, season end (Julian dates), number of seasons to simulate thunderstorms, probabilities of SE thunderstorms for each region (adjusted by the AAF), persistence of thunderstorms from one day to the next, and chances for more than one event on the same day.

DROM

The DROM subroutine contains three subroutines of its own. These are SE, SW, and FRONTAL (fig. 13), which represent sources of moisture from the principle sources, the Gulf of Mexico, the Pacific Ocean, and weather fronts, respectively. The SE and SW routines simulate thunderstorms, whereas FRONTAL simulates constant low-intensity rainfall over the specified area. These systems can occur in any combination. Watershed location will dictate which combinations are favored. The SE and SW thunderstorms are more massive when combined with frontal events.

The SE subroutine determines whether any storms involving this system will occur based on the thunderstorm probability curve for the watershed region, latitude, longitude, and elevation. The SE rainfall probability curves at sites other than the base site of the region for which the probabilities were

developed are calculated based on latitude, longitude, and elevation. Also, the SE computations are the only parts of DROM that are affected by the AAF term (see above).

The SW and FRONTAL subroutines are very similar. Both have a constant probability for rain on a day when there is no rain on the previous day. If there is rain, the following day has an increased chance of rain. The chance of rain after two successive rainy days is decreased and so on. The equations used to calculate the daily probability for SW and FRONTAL have different constants; FRONTAL does not include watershed elevation, whereas SW does. Also, a constant depth is generated when FRONTAL is called, whereas SW calls for thunderstorm rainfall.

SPAR

SPAR reads in spatial parameters (cell diameter, mode distance between cells, number of cells) and calculates shape parameters to be used in the IMSL canned routines GGPOSH (a pseudorandom Poisson distributed deviate), GGAMA (a pseudorandom gamma distributed deviate), and GGNOF (a pseudorandom normally distributed deviate). Parameters and statistics are read in and printed out. These are used in the SDOR subroutine.

SDOR

The SDOR subroutine is the most complex part of the SATDOR program. There are four main subroutines in SDOR with several minor subroutines (fig. 13). Basically, SDOR generates and distributes rainfall to gages on the watershed, depending upon whether the event is a thunderstorm, frontal storm, or both. This is done by using a combination of subprograms particular to a storm type. The four main subroutines are:

(1) DTHUND - Generates and distributes thunderstorm rainfall.
(2) DFRONT - Generates frontal rainfall.
(3) FDEPTH - Distributes frontal rainfall.
(4) PRINTER - Prints results of the three previous subroutines.

DTHUND has three subroutines and one function routine of its own; DIRDIST and CDEPTH generate location of storm cell centers as well as depths at the cell centers. DIST is a function of DIRDIST and calculates distance between cells using GGNOF. The SPAR subroutine reads in average cell radius for different storm types. The distance between cell centers cannot exceed the cell diameter. The number of cells per storm is generated by NOCS using GGPOSH. If the number is less than 3 or greater than 12, NOCS regenerates a number until it is within this range. At present, storm duration is a constant (for each storm combination) times the number of cells. GCDEPTH is a function that distributes thunderstorm rainfall to each gage according to the distance between the gage and the cell centers.

[illegible] GGAMA [illegible] generate frontal storm depths, and FDEPTH distributes [illegible] no storm pattern or variation in [illegible] errors for larger watersheds, but prob- [illegible] routine could be modified to allow for [illegible] t, and any other topographical influence.

PRINTER prints results of the SDOR subroutines.

TPAR

TPAR reads in the temporal parameters and calculates shape parameters for the canned subroutine GGNOF and prints out the parameters and statistics. These values are used in the TDOR subroutine.

TDOR

Thunderstorm rainfall events are temporally distributed by TDOR using the functions BTTH and ETTH. The subroutine TDOR also handles the temporal distribution of frontal events. The set of statistics for the starting time, deviations, and duration will vary on storm type and if there is more than one storm per day.

BTTH varies with the number of storms per day and with which storm is assigned a beginning time (the second storm must occur after the first is finished). Results are checked to see if they are valid and, if not, regenerated. ETTH generates the end time of thunderstorms by indirectly using GGPOSH and the number of cells.

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